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Nonuniformities in compact heat exchangers—scope for better energy utilization: A review

Sanjay Kumar Singh, Manish Mishra*, P.K. Jha

Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Roorkee 247667, India

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ABSTRACT

The present paper deals with a review of the nonuniformities present in compact heat exchangers in terms of temperature and flow and their effect on the performance of different energy transfer equipment. The understandings of flow distribution and flow pattern at the entrance of compact heat exchanger and prediction of the behavior of heat exchanger have also been reviewed. Different models for temperature and flow nonuniformities have been discussed. Investigations on steady state and transient thermal performance due to nonuniformity of temperature and flow have also been discussed. Focus has also been given on design aspects of the inlet headers and distributors mainly responsible for nonuniformities. Experimental studies have been cited to evaluate the effects of distributor's configuration parameter on the fluid flow maldistribution in the plate-fin heat exchanger. Effect of nonuniformities on both two- and three-fluid heat exchangers with phase change and with physical property variations has also been reported. The deterioration of thermal performance of a solar collector due to flow nouniformity effect has also been discussed.

Contents

1. Introduction

Heat exchanger is a device used for transfer of thermal energy (enthalpy) between two or more fluids, between a solid surface

* Corresponding author. Tel.: +91 1332 285135; fax: +91 1332 285665.
E-mail addresses: mmishfme@iitr.ac.in, mishra_md@yahoo.com (M. Mishra).

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Nomenclature

A	area of heat transfer, (m^2)
a, b	distance from origin 'o'
CFD	Computational Fluid Dynamics
c_p, c_v	specific heat, (J/kg K)
D_h	hydraulic diameter
d_e	equivalent diameter
E	capacity rate ratio
f	friction factor
G	mass flux velocity
h	heat transfer coefficient, (W/m^2 K)
h/H	distributor configuration parameter
k	thermal conductivity of separating sheets, (W/m-K)
L	heat exchanger length, (m)
l	vertical distance
m	maldistribution parameter
m, n	exponents
NTU	Number of Transfer Unit
N_a	$(\eta hA/mc)_b$
Nu	Nusselt number

Greek symbols

α	flow maldistribution factor, $\alpha = m'/m$
β	ratio of equivalent diameter
$\beta(p, q)$	Beta function
τ	time, (s)
Φ	local flow nonuniformity parameter
ψ	nonuniformity factor
τ_2	thermal performance deterioration factor
η	ratio of extreme velocities
ψ	$=(Mc)_{w1}/(Mc)_w$
μ	dynamic viscosity, (N-s/m^2)

Superscripts

1, 2	separating wall 1 and 2
B	constant

Subscripts

a, b, c	fluid a, b and c
Ave	average
Cp	constant property
Ex	exit
i, in	inlet
N	number of channels
PIV	Particle Image Velocimetry
Pr	Prandtl number
P_e	Peclet number
P	pressure, (N/m^2)
p, q	parameters used in Eq. (16)
Q	mass flow rate, (m^3/s)
R	conductance ratio
R_e	Reynold's number
S	flow maldistribution parameter
T	dimensionless temperature
$\overline{T}$	dimensionless mean temperature
T	temperature
$\bar{t}$	mean temperature
V	heat capacity ratio $= LA_c\rho c/Mc_w$
ϑ	flow passage velocity
w	fluid velocity
X	$=(\eta hA/mc)_b x/L_x = N_a(x/L_x)$
Y	$=(\eta hA/mc)_b y/L_y = N_a(y/L_y)$
x, y	x and y coordinates
$\dot{\phi}(\Theta)$	perturbation in inlet temperature for fluid 'b'
Λ	longitudinal heat conduction parameter
$\varepsilon_0, \varepsilon_2$	exchanger heat transfer effectiveness
θ	dimensionless time
δ	equivalent thickness of separating sheet,
ζ_c	channel friction coefficient
ζ_g	pressure loss coefficient of perforated grid
ρ	density, (Kg/m^3)
ϕ	$=(\eta hA)_{b-w1}/(\eta hA)_b$
Φ	equivalent diameter
m, n	exponents
Max	maximum
Min	minimum
Out	outlet
W	separating wall
x, y	direction

and a fluid, or between solid particulates and a fluid, at different temperatures and in thermal contact, usually without external heat and work interactions.

Compact heat exchangers are characterized by a comparatively large area density, i.e. the ratio of heat transfer surface area to heat exchanger volume. Their large area density, indicating small hydraulic diameter for fluid flow, results in a higher efficiency than a conventional tubular heat exchanger in a significantly smaller volume. Compact heat exchangers are used in a wide variety of applications like automobile radiators, condensers, electronic cooling devices, air-conditioning systems, recuperators, regenerators, heat exchangers used in cryogenics, etc.

A gas-to-liquid heat exchanger is referred to as a compact heat exchanger if it incorporates a heat transfer surface having a surface area density above 700 m^2/m^3 on at least one of the fluid sides, which usually has gas flow. A liquid/two-phase fluid heat exchanger is referred to as a compact heat exchanger if the surface area density is above 400 m^2/m^3 (Shah and Sekulic [1]). Human lungs are one of the most compact heat exchangers, having an area density of about 17,500 m^2/m^3.The performances of compact heat exchangers including heat transfer enhancement mechanisms, their advantages and limitations have been reviewed by Li et al. [2]. A compact plate-fin heat exchanger assembly with its detailed view and a few arrangements of compact heat exchanger have been given in Fig. 1 and Fig. 2, respectively.

2. Nonuniformity

The temperature and fluid flow are usually nonuniform under the actual operating conditions in a heat exchanger. The situations become more serious when the nonuniformities in the flow and/or

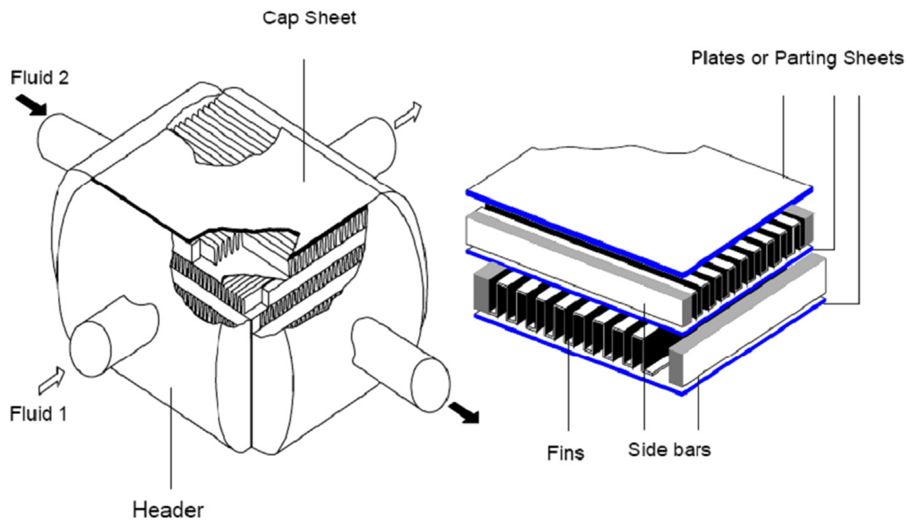

Fig. 1. Compact plate-fin heat exchanger assembly and its detailed view.

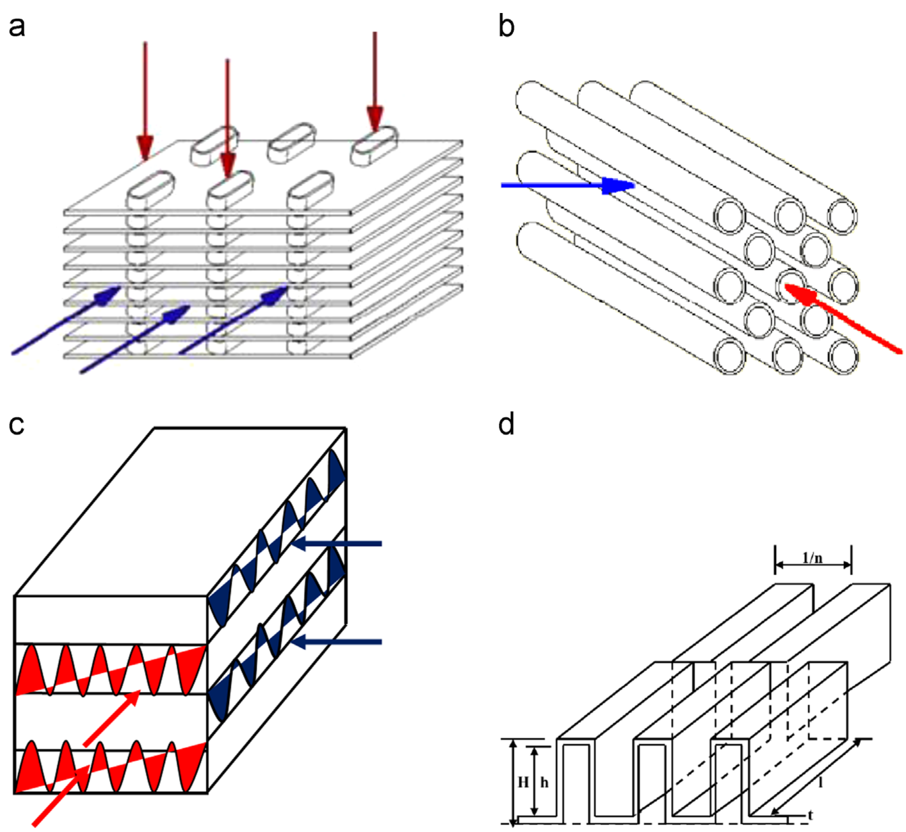

Fig. 2. Compact heat exchangers with (a) Tube-fin, (b) Tubular flow, (c) Triangular fins, and (d) Offset strip-fins.

temperature starts right at the entry and continue inside the core. So, the thermal response of heat exchangers with temperature and flow nonuniformity will help the designer rely on a solution, for the problems, very useful in thermal and stress analysis for design of such equipments.

The nonuniformities in flow and temperature may be induced due to various reasons.

As described by Shah and Sekulic [1], flow nonuniformity can be induced by

- Heat exchanger geometry (mechanical design features such as basic geometry, manufacturing imperfections, and tolerances), and
- Heat exchanger operating conditions (such as viscosity or density-induced maldistribution, multi-phase flow, and fouling).

Furthermore, geometry induced flow nonuniformities can be classified as

- Gross flow nonuniformity,
- Passage-to-passage flow nonuniformity, and
- Manifold-induced flow nonuniformity.

The most important operating condition affecting the performance is viscosity induced nonuniformity and associated flow instability.

Apart from maldistribution in flow, nonuniformity may also exist in fluid temperature at different passages of compact heat exchanger as hot and cold fluids usually enter their respective layers of the core through the header and flow distributors. In general the inlet temperatures of all the fluids are assumed to be uniform. There may also be the possibility that the fluid entering the core has more than one stream and complete mixing may not take place before entering the heat exchanger. Similarly, the inlet temperature may become nonuniform when two or more fluid streams at different temperatures enter the heat exchanger core without complete mixing as given by Mishra et al. [3]. Thus, the steady state thermal performance is significantly affected due to nonuniformity of temperature [4].

Nonuniformities may also be caused due to two-phase or multi-phase flow in the narrow channels of compact heat exchangers. The distribution of different phases and their different flow velocities cause nonuniformities in compact heat exchangers. Two-phase flow maldistribution [1] may be caused and/or influenced by different phenomena such as phase separation, oscillating flows, variable pressure drop (density-wave instability), flow reversals, and other flow instabilities. For single-phase applications, the heat transfer coefficient changes along the flow length of the exchanger. Compact heat exchangers are also used for condensation and boiling heat duties where the phase change occurs in the small channels. Hence, nonuniformities play an important role in the performance of such heat exchangers.

2.1. Temperature nonuniformity

The temperature nonuniformity in a compact heat exchanger plays an important role in its performance. There are possibilities that the fluid streams may enter the heat exchanger with different temperature levels. The degradation in performance may occur when fluid streams are not well mixed before entering the compact heat exchanger.

The nonuniformity in fluid inlet temperature has been first investigated for crossflow heat exchanger and radiator by Chiou [5,6]. It was reported that temperature nonuniformity further worsens the heat exchanger performance deterioration caused due to flow maldistribution alone. It has been found up to 12% reductions in the heat exchanger effectiveness due to nonuniform inlet temperature [7]. Chiou [8] further proved that higher temperature nonuniformity factor will produce higher performance deterioration. The results also show that the deterioration factor reduces for increase in the values of NTU, i.e., with lower mass flow rates.

A numerical investigation by Brandemuehl and Banks [9] has been carried out to understand the performance of a countercurrent, rotary heat exchanger operating with either step increase or nonuniformity in inlet fluid temperature. It has been found that the steady state effectiveness can be either increased or decreased with different arrangement of nonuniform distribution of inlet temperature. In another numerical investigation by Kou and Yuan [10], two hot streams with different temperature levels were taken on one side of the heat exchanger and one cold stream was taken on the other side of the heat exchanger. The governing equations were discretized using finite difference equation, the numerical solution was compared with the analytical solution of Kays and London [11] and it was found that they are in good agreement. It was found that the thermal performance increases due to the specified nonuniform inlet temperature in crossflow heat exchanger. Investigations regarding nonuniform inlet temperature were further reported by Yuan and Kou [12] for finding out the effects of longitudinal conduction in crossflow heat exchanger. Thermal performance of a direct transfer type, single pass, crossflow heat exchanger with nonuniform inlet temperature for steady condition has been investigated. The mean exit temperatures and effectiveness were obtained numerically considering four kinds of arrangement to study the effects of longitudinal wall conduction. The results reveal that the longitudinal wall conduction deteriorates the thermal performance for all four arrangements.

2.2. Flow nonuniformity

It is well known that poor flow distribution in parallel channels causes degradation in heat exchanger performance. Fleming [13] investigated the effect of flow maldistribution on performance deterioration. The reduction in performance is particularly severe in balanced flow cryogenic heat exchangers of very high thermal effectiveness.

The effect of flow maldistribution on heat transfer was estimated by Shah [14] and it was found that flow maldistribution was generated by velocity profile in inlet ducts. Muller [15] investigated the effects of several types and effects of maldistribution in heat exchangers thermal performance. It has been found that most heat exchangers show only a small reduction in performance for turbulent flow compared to the reduction in performance in case of laminar flow. In one of the earliest studies on flow maldistribution, London [16] investigated the effect of nonuniform air passages, arising due to manufacturing tolerances, on the performance of plate-fin heat exchanger. It has been found that manufacturing tolerance has a significant influence on the overall heat transfer and flow friction behavior. Similar work was carried out by Mondt [17] and Shah and London [18].

The effect of flow nonuniformity for single-pass crossflow heat exchanger was first investigated by Chiou [19] under steady state conditions. Thermal performance deterioration of the heat exchanger due to the effects of four typical models of flow nonuniformity has been presented for various heat exchanger designs and operating conditions. Flow nonuniformity factor has been developed as the principal parameter for the determination of performance deterioration. Chiou [20] further used the numerical method for determining the deterioration of thermal performance of a solar collector due to flow nonuniformity at steady state condition. The collector efficiency and deterioration in performance were determined for various collector designs and operating conditions.

A method for predicting dynamic performances of parallel and counterflow heat exchangers subjected to the effect of flow maldistribution was developed by Xuan and Roetzel [21]. Method of numerical inversion of the Laplace transform has been used to determine the temperature profiles. Comparisons between the calculated and experimental temperature profiles were also carried out. The Laplace transform method along with the finite temperature difference method has also been applied by Roetzel and Xuan [22] to analyze the effects of flow maldistribution of crossflow heat exchangers and to calculate the outlet temperature response to flow rate disturbances.

Effects of flow nonuniformity in different specific types of heat exchangers have been mentioned as follows.

2.2.1. Plate-fin compact heat exchanger

Ranganayakulu et al. [23] presented the effects of two-dimensional nonuniform inlet fluid flow distribution of both hot and cold fluids in a crossflow plate-fin compact heat exchanger using the finite element method. Mathematical equations were developed to generate different flow maldistribution models. Pressure drops and their variations were also calculated. It was found that the performance deteriorations and variation in pressure drops are quite significant in applications having maldistribution effects. Again using the finite element method, Ranganayakulu and Panigrahi [24]

analyzed a crossflow two-pass compact plate-fin heat exchanger for the effects of nonuniform fluid-flow due to inlet headers. The heat exchanger effectiveness, pressure drops and performance deterioration due to the effects of flow nonuniformity were calculated. Hot side inlet and outlet headers were modified to improve the effectiveness and to reduce the pressure drop.

Zhang and Li [25] numerically investigated the flow nonuniformity in a plate-fin heat exchanger using CFD. They suggested two modified headers with a two-stage distributing structure to reduce the flow nonuniformity. It was proved by them that the fluid flow distribution in plate-fin heat exchanger will be more uniform if the ratios of outlet to inlet equivalent diameters for both headers are kept equal. Furthermore, the effects of header configurations were experimentally investigated by Jiao et al. [26]. The concept of second header configuration for a plate-fin heat exchanger has been put forward and the equivalent area of header equivalent diameter is defined in order to describe the characteristics of the header. The results show that the optimization of header configuration can effectively improve the flow distribution in a plate-fin heat exchanger. The effect of header on flow distribution in a plate-fin heat exchanger was also numerically studied by Wen and Li [27] using FLUENT. The concepts of using baffles with small holes of three different diameters were studied showing improvement in the flow distribution. Effects of distributor configuration on flow maldistribution in plate-fin heat exchangers were experimentally investigated by Jiao et al. [28] and Jiao and Baek [29]. The effect of nondimensional distributor configuration parameter 'h/H' on flow maldistribution was analyzed. Correlation between Reynolds number and distributor configuration parameter has also been developed.

Using Particle Image Velocimetry (PIV), Wen et al. [30] investigated the characteristics of flow field at the entrance of a plate-fin heat exchanger. On the basis of the experiments, they suggested that punched baffle could improve fluid flow distribution in the header.

Ranganayakulu et al. [31] and Ismail et al. [32] analyzed two typical compact plate-fin heat exchangers using CFD for flow maldistribution effects with ideal and real cases. Suitable baffle plates were recommended to be placed at the inlet of the core for improvement in flow distribution, based on study. It was also proved that flow nonuniformity drastically reduces due to the implementation of baffle plates.

Zhang [33] mainly studied the effects of channel pitch in plate-fin compact heat exchanger cores to show the importance of flow maldistribution. By treating the plate-fin core as a porous media, a CFD code was used to calculate the flow distribution. Heat transfer model in the plate-fin channels has been set up in the investigations. It was observed that when the channel pitch is larger than 2 mm, the flow maldistribution becomes serious and the effect of nonuniformity has to be considered. It was also found that the thermal performance was deteriorated by 10–15%.

As further reported by Zhang [34], heat mass exchangers are crucial for the prevention of epidemic respiratory diseases such as H1N1 (swine flu). CFD code was generated to predict flow maldistribution data and finite difference scheme was used for calculations. The results indicate that when the channel pitch is below 2.0 mm, flow distribution is quite homogeneous and the deteriorations in sensible and latent performance due to flow maldistribution can be neglected. However, when the channel pitch is larger than 2 mm, the maldistribution is quite significant and 10–15% increase in thermal deterioration factor and 20–25% increase in latent deterioration factor could be found. Mass transfer deteriorates much more than the heat transfer due to the larger mass transfer resistance through membranes.

Hoffmann-Vocke et al. [35] experimentally determined the hydraulic analysis of the plate-fin heat exchanger without taking into account the effect of maldistribution on hydraulic efficiency. It was observed that flow maldistribution spreads due to heat exchanger resistance.

2.2.2. Tube-fin heat exchanger

The thermal performance deterioration due to nonuniformity in flow velocities on tube-fin heat exchanger used as condensers or evaporators has been studied by Fagan [36]. It has been found that a larger deviation from the average flow velocity will result in a larger thermal performance deterioration.

Further, Chwalowski et al. [37] and Domanski [38] experimentally observed that the flow nonuniformity on the air-side can induce maldistribution of refrigerant flow and consequently will increase the thermal degradation. It has been observed that air-side nonuniformity altered the distribution of refrigerant in the circuits of the exchanger coil. Thereby, the varying degrees of superheat at the circuit outlets lead to a large reduction of cooling capacity. Chwalowski et al. [37] observed a reduction of up to 30% in the cooling capacity. Similar findings were also obtained by Kirby et al. [39] for their study on the effect of airflow nonuniformity of evaporator performance. Concentric-tube counterflow heat exchanger with fins was analyzed by Ratts [40] to quantify the effect of flow maldistribution.

Using the finite element method, Ranganayakulu and Seetharamu [41] investigated the crossflow plate-fin and tube-fin, counterflow and parallel flow plate-fin compact heat exchanger. The effect of longitudinal wall conduction on thermal performance and consequently performance degradation has been discussed for various design and operating conditions. It was found that performance degradation becomes higher when the longitudinal wall conduction is large.

Aganda et al. [42] investigated the effects of maldistribution in fin-tube heat exchangers. They considered maldistribution to take place on the air-side through the fin passages and on the liquid side in the tube circuits. Their findings indicated the dependence of the degradation on the mean and standard deviation of the flow maldistribution profile.

Experimental investigations have been carried out by Lee et al. [43] on fin-tube evaporator coils. The main objective was to manipulate the degree of refrigerant superheat at the outlet of the heat exchanger so as to compensate the thermal performance degradation due to flow maldistribution. Choi et al. [44] also experimentally investigated the effects of nonuniform airflow and refrigerant distribution on the capacity degradation of finned-tube evaporator. It was found that the capacity degradation due to refrigerant maldistribution can be as high as 30%. Similar analysis was also carried out by Koern et al. [45].

Using the finite element method, Ranganayakulu and Seetharamu [46] further investigated the combined effects of longitudinal wall conduction, flow and temperature maldistribution on the thermal performance of crossflow tube-fin compact heat exchanger. A mathematical model has been developed considering maldistribution, and investigation for thermal performance degradation in design and operating variables has been presented.

Chin and Raghavan [47,48] presented the influence of the statistical moments of probability density function like standard deviation, for airflow maldistribution on the thermal performance of tube-fin heat exchanger. They also investigated the effects of various geometrical parameters and found that the thermal performance is affected by mean, standard deviation and skew except kurtosis which has no significant effect. They proposed a new set of correlations to predict the degradation effect of flow maldistribution on wavy fins. Further, Chin [49] analytically quantified the thermal performance degradation effects in an arbitrary heat exchanger with respect to flow maldistribution statistical moments in the presence of both flow and temperature

maldistribution. It has been found that the magnitude of thermal performance degradation is dependent on the shape index *S* and the statistical moments of the probability density function of the velocity distribution. Shape index *S* (so named as it depends on the shape of both the nonuniform profiles) is a new parameter introduced by the author which characterizes the relationship between the flow and temperature fields.

Koern et al. [50] numerically investigated the refrigerant and airflow maldistribution in fin and tube evaporators for residential air conditioning. Evaporator and condenser as individual maldistribution source have been investigated in an independent manner. Inlet liquid/vapor phase distribution, feeder tube bending and airflow distribution have been considered as maldistribution source. They found that maldistribution reduces the cooling capacity and coefficient of performance of the system. Further, Koern et al. [45] numerically investigated the compensation of flow maldistribution in multi-channel fin-and-tube evaporators for residential air-conditioning. The compensation for decrease in cooling capacity and coefficient of performance due to flow maldistribution has been performed by the control of the superheat in the individual channels.

Mao et al. [51] numerically studied the effect of airflow maldistribution on heat transfer and pressure drop of the multi-louvered fin and tube heat exchanger using the finite volume method. It has been found that the airflow maldistribution affects the condensation capacity, refrigerant pressure drop, and fan power consumption as well. The study was expected to be helpful in designing and sizing an optimum air arrangement for making the flow more uniform in distribution.

For the given maldistribution in tube side, Roetzel and Ranong [52] numerically calculated the axial temperature profiles. The comparison between parabolic and hyperbolic dispersion model was carried out for the same maldistributions and it was found that the hyperbolic model gives a better axial temperature profile.

Sahoo and Roetzel [53] also investigated the effect of flow maldistribution in shell and tube heat exchangers for steady-state and transient processes using dispersion models. It has been observed that the hyperbolic model is the best suited one as it compares well with the actual calculations.

2.2.3. Plate heat exchanger

Bajura and Jones [54] presented both analytically and experimentally the effect of unequal distribution of fluid from port to channel in four types of manifold systems. The proposed method of analysis can be used for general application for predicting the performance of flow distribution systems.

An analytical study was conducted by Bassiouny and Martin [55] to calculate flow distribution and pressure drop in plate heat exchangers. For the U-type arrangement with both inlet and outlet ports on the same side, it was found that a very low flow rate or even no fluid flow occurs in some of the channels for large positive or negative values of a general characteristic parameter '*m*'. Further, Bassiouny and Martin [56] extended their work for Z-type arrangement. The inlet and outlet ports were considered in opposite sides. The analysis shows that total pressure drop in plate heat exchanger is practically the same for both U-type and Z-type arrangements.

Considering maldistribution of flow in a plate heat exchanger, Heggs and Scheidat [57] developed a mathematical model taking into account the heat transfer in individual plate channels. They observed that flow maldistribution effect was insignificant with less than 20 plates. However, the adverse effect has been found on the thermal performance by the end channels; thus, a proper consideration is to be taken while designing channels.

Thonan et al. [58] analyzed that misunderstanding of the consequences of a non-uniform flow distribution on thermal and hydraulic performances can lead to the poor design of the heat exchanger. It has been found that the pressure drop is largely affected due to the non-uniform flow distribution as compared to the thermal performance.

Lalot et al. [59] numerically investigated the effect of flow non-uniformity on the performance of plate heat exchangers. They found the optimum location of perforated grid in the inlet header and concluded that gross flow maldistribution leads to a loss of effectiveness up to 25% for velocity ratios up to 15. A simple way has also been suggested to homogenize the flow distribution and to calculate, the velocity ratio, the ratio of the highest velocity to the lowest velocity, with good accuracy. Similar to the results obtained by [59], Luo et al. [60] have also observed that the nonuniformity influences the efficiency of the heat exchangers to a large extent.

The effect of port to channel flow maldistribution on the pressure drop across a plate heat exchanger has been experimentally studied by Rao and Das [61]. The results show that the major cause of maldistributed flow is channel resistance. The result also indicates that under identical conditions, maldistribution is more severe in Z-type plate heat exchanger compared to U-type plate heat exchanger. They suggested that port size should be kept at its maximum permitted level by manufacturing and heat transfer considerations to keep the flow maldistribution at its minimum. The total pressure drop across the heat exchanger is mainly dependent on flow rate, port size and number of channels. Rao et al. [62,63] also presented the steady state analysis on the effect of flow distribution to the channels on the thermal performance of a plate-heat exchanger. It has been found that the maldistribution in flow brings about an increase in pressure drop and decrease in thermal performance of heat exchanger.

An analytical study based on Laplace Transform for the transient behavior of plate heat exchanger with maldistribution effects has been carried out by Srihari et al. [64]. They presented the effects of flow maldistribution and of conventional heat exchanger parameters on the temperature transients of both U-type and Z-type configurations. They found that the effect of flow maldistribution is very significant in deteriorating the thermal performance as well as on the characteristic features of the dynamic response of the heat exchanger.

Bobbili et al. [65] carried out an experimental investigation to find out the flow and the pressure difference in plate package heat exchangers for a wide range of Reynolds number (1000–17,000). In their study, plates with low corrugation angle have been used for different channels. Water has been used as the working fluid for both hot and cold sides. A simplified non-dimensional channel velocity has been suggested based on the channel pressure drop and the mean channel pressure drop of plate package, so as to measure the deviation of the particular channel flow rate from its mean value. The flow maldistribution was found to increase with increasing overall pressure drop in the plate heat exchangers.

Subjected to a step variation in flow, a predictive model has been presented by Dwivedi and Das [66] to suggest the transient response of plate heat exchangers. The effect of the port to channel maldistribution on the performance of plate heat exchangers was observed. A parametric study has been presented showing the effects of NTU and heat capacity rate ratio on the transient response of the plate heat exchanger subjected to flow perturbation. An experimental study has also been carried out to verify the theoretical model.

Tereda et al. [67] experimentally determined the dependence of flow distribution on port dimension and flow rates for U-type and Z-type flow configurations of plate heat exchanger. The experimental results were compared and found to be reasonably in agreement with the theoretical model given by Baassiouny and Martin [55,56].

Srihari and Das [68] studied the transient response of multi-pass plate heat exchangers considering flow maldistribution from

port to channels. The solution for each module has been obtained analytically using Laplace transform followed by numerical inversion. It has been observed that the transient characteristics such as response delay, asymptotic value and time constant are strongly dependent on the flow arrangement, maldistribution and backmixing characterized by axial dispersion. Srihari and Das [69] further studied experimentally and numerically to investigate the effect of port to channel flow maldistribution on the transient response of plate heat exchangers with U-type and Z-type flow configurations. It has been found that transient features such as time constant, initial delay and response time are affected due to flow maldistribution. It was also experimentally found that Z-type flow configuration is more strongly affected than U-type flow configuration in plate heat exchanger. It has also been observed that the numerical results found through the finite-difference method agree well with the experimental observations.

An experimental analysis by Shaji and Das [70] dealt with the effect of flow maldistribution on the transient temperature response of U-type plate heat exchangers. Experiments were carried out with uniform and non-uniform flow distributions for various flow rates with different numbers of plates. The variations of heat transfer coefficients have also been taken into consideration. They concluded that flow maldistribution and backmixing, which lead to axial dispersion, are two different physical phenomena and should not be clubbed together as the earlier models of plate heat exchangers have proposed.

Separating the flow maldistribution effects from fluid backmixing Shaji and Das [71] further proposed a new mathematical model to determine heat transfer and dispersion coefficients in plate heat exchanger using the single blow transient testing technique. The numerical data were also validated with the experimental results for plate heat exchangers with different chevron angles.

3. CFD studies

Computational fluid dynamics (CFD) has also been used to determine the effect of fluid flow maldistribution in various types of compact heat exchangers. The simulation results obtained using CFD also give quality solutions, indicating it to be an important tool for predicting the performance behavior of compact heat exchangers. Some of the studies employing CFD as a tool to estimate the performance of different kinds of compact heat exchangers have been reviewed and presented.

Grijspeerdt et al. [72] used CFD Code FINE-Turbo with Lomax turbulent stress model for the simulation of plate heat exchangers to determine the effect of fluid flow maldistribution. It was observed that recirculation bubbles are formed, which hinder steady flow.

Zhang and Li [25] used CFD Code FLUENT with SIMPLE-pressure-velocity coupling scheme, standard k–ε turbulence model and finest mesh of 150,000 cells. They simulated the inlet configuration to optimize the header design in a plate-fin heat exchanger for fluid flow maldistribution. Wen et al. [30] also studied plate-fin heat exchangers using CFD code FLUENT with Semi Implicit SIMPLER-pressure–velocity coupling scheme, second-order upwind turbulence model with the finest mesh of 245,817 cells. They incorporated baffles with holes to uniformly distribute the fluid inside core.

Wasewar et al. [73] used CFD Code FLUENT 6.1, segregated solver, k–ε turbulence model, GAMBIT v2.1 meshing software, structured mesh tri-tetra and a grid of 2,000,000 cells to simulate plate heat exchanger for fluid flow maldistribution. They found that maximum velocity of flow occurs at the center and it decreases sideways. Incorporating a large header height, they were able to decrease the maldistribution by 70%.

Further, Zhang [33] used CFD code FLUENT, Pressure–Velocity Coupling Scheme- SIMPLE, GAMBIT meshing scheme with coarse tetrahedral and hexahedral 160,837 cells to simulate plate-fin heat exchanger for fluid flow maldistribution. They studied three different channel pitches and found that channel pitch with large dimensions was more responsible for maldistribution.

Habib et al. [74] numerically simulated the effect of flow maldistribution in air-cooled heat exchangers using CFD. The effects of various parameters like number of nozzles, nozzle diameter, and inlet flow velocity and also the incorporation of a second header have been investigated. It has been found that by reducing the nozzle diameter by 25%, flow maldistribution increases by 25%.

CFD studies have also been carried out by Agrawal et al. [75] to model the effect of flow maldistribution on the performance of a catalytic converter. Flow maldistribution has been observed inside monolith channels. It was found that flow maldistribution significantly affects the conversion in the catalytic converter.

Bansode et al. [76] studied the effects of different types of flow maldistribution on heat and mass transfer in PEM fuel cell. The numerical study was carried out using FLUENT solver and governing equations were solved using the control volume approach.

4. Different models of nonuniformities

Some of the mathematical models representing flow and temperature nonuniformities have been discussed for comparison.

4.1. Flow nonuniformity models

Chiou [19] considered a two-dimensional flow nonuniformity concept (Fig. 3) for investigating the thermal performance of direct transfer type heat exchangers. A local flow nonuniformity parameter to specify the degree of flow nonuniformity has been introduced as given in Eq. (1).

$$\Phi = \frac{\text{actual local mass flow rate}}{\text{average value for the uniformly distributed fluid flow}} \tag{1}$$

A numerical method using the successive substitution technique was developed to investigate the effect of flow nonuniformity on the thermal performance of single-pass crossflow heat exchangers. An exchanger thermal performance deterioration factor (τ_2) has been introduced to illustrate the influence of two-dimensional flow nonuniformity on the thermal performance of heat exchanger as defined in Eq. (2).

$$\tau_2 = \frac{\varepsilon_0 - \varepsilon_2}{\varepsilon_0} \tag{2}$$

For the convenience of representing the flow maldistribution, Chiou [19] had used the concept of standard deviation to define the non-uniformity, Φ, as in Eq. (3).

$$\Phi = \sqrt{\sum_{i=1}^{N} \left(\beta_i - \bar{\beta}\right)^2 / N}, \tag{3}$$

where N is the number of tubes in the parallel flow heat exchanger, β_i is the flow in ith channel, and $\overline{\beta}$ is the average flow ratio for the all tubes, $\left(\sqrt{(\sum_{i=1}^{N} \beta_i)/N}\right)$.

The larger value of Φ indicates the higher non-uniformity.

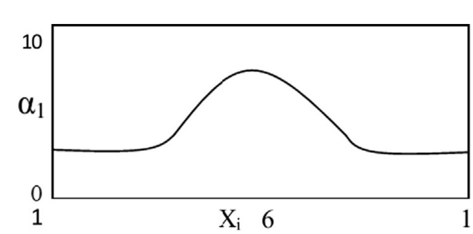

Fig. 3. Chiou's [19] two-dimensional flow distribution model.

A mathematical model, based on the concept of Fourier series, has been developed by Ranganayakulu et al. [23] to generate the nonuniformity at the heat exchanger inlet of either hot side or cold side. The heat exchanger core frontal face is considered as a rectangular domain having edges 2a and 2b in the x–y plane. The length with respect to origin 'o' is $x=-a$ to a and $y=-b$ to b. The equation for the fluid (cold or hot) at the heat exchanger inlet has been given by Eq. (4).

$$\frac{\partial^2 W}{\partial x^2}+\frac{\partial^2 W}{\partial y^2}=\frac{\partial P}{\mu \partial z}=\text{a constant} \tag{4}$$

$$\text{at, } x=\pm a, W(\pm a, y)=0 \tag{5}$$

$$\text{at, } y=\pm b, W(x, \pm b)=0 \tag{6}$$

where pressure gradient is assumed to be constant in z-direction of the fluid velocity. The solution to Eq. (4) for boundary conditions (5) and (6) is used to calculate the actual local mass flow rates at the entry of the exchanger inlet duct.

Further, Ranganayakulu and Seetharamu [41] studied the combined effects of longitudinal heat conduction, temperature nonuniformity and flow nonuniformity using a finite element method for a crossflow tube-fin compact heat exchanger. Using Eqs. (4–6), different types of flow/temperature nonuniformity models can be generated by distorting the velocity profile by keeping average mass flow rate as unity. Fig. 4 represents a typical flow/temperature nonuniformity model with the highest magnitude of maldistribution. The fluid flow velocity at the wall of the inlet duct is zero while it increases away from the wall.

Following the concepts of Fraas [77], Lalot et al. [59] studied the effect of flow nonuniformity on the performance of heat exchangers like condensers, crossflow and counterflow heat exchangers. They have shown that gross flow maldistribution leads to a loss of effectiveness up to 7% for condensers and counterflow heat exchangers and up to 25% for crossflow heat exchangers, for a maximum velocity ratio of 15. The ratio of extreme velocities 'η' in terms of Pressure loss coefficients 'ζ' has been defined in Eq. (7).

$$\eta=\sqrt{\frac{(\zeta_1+\zeta_2)_{\max}+\zeta_g}{(\zeta_1+\zeta_2)_{\min}+\zeta_g}} \tag{7}$$

It was found that with the increase in velocity ratio, the effectiveness ratio decreases for condensers, crossflow and counterflow heat exchangers. They also found that the effect of maldistribution is much more important for crossflow heat exchanger than that for condensers and counterflow heat exchangers.

The effect of header configuration was experimentally investigated by Jiao et al. [26]. They experimentally presented the effects of inlet pipe diameter ($\Phi_{1(\text{in})}$), the first header's diameter of equivalent area ($\Phi_{2(\text{out})}$), and the second header's diameter of equivalent area ($\Phi_{2(\text{in})}$) and ($\Phi_{2(\text{out})}$) on the flow distribution in plate-fin heat exchangers. The concept of second header configuration has been conceptualized. The equivalent area of header and its equivalent diameter are defined in order to describe the characteristics of the header configuration. The experimental results show that the optimization of header configuration can effectively improve the flow distribution in plate-fin heat exchanger, especially in the direction perpendicular to the inlet flow. The experimental results also show that the flow velocity distribution will be uniform, when $\Phi_{1(\text{out})}/\Phi_{1(\text{in})}$ is equal to $\Phi_{2(\text{out})}/\Phi_{2(\text{in})}$. The correlation between the dimensionless flow maldistribution parameter 'S' and the Reynolds number for the heat exchanger core is deduced for different header configurations.

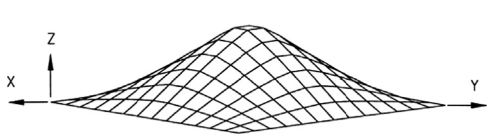

Fig. 4. Flow nonuniformity model A0 [41].

Zhang and Li [25] numerically investigated a plate-fin heat exchanger and suggested modified headers with two-stage distributing structure to reduce the flow nonuniformity using CFD. They simulated the inlet configuration to optimize the header design. The ratio of equivalent diameter was used, as is defined by Eq. (8).

$$\beta=\frac{[\phi_{1,\text{out}}/\phi_{1,\text{in}}]}{[\phi_{2,\text{out}}/\phi_{1,\text{in}}]} \tag{8}$$

where ϕ is equivalent diameter and β is the ratio of equivalent diameters at inlet and that of outlet. The results showed that the flow distribution is critical in vertically upward direction for the header design currently used in the industries (Fig. 5). Based on the conclusion, two optimized headers having two-stage-distributing structures were proposed and verified through simulation.

Rao and Das [61] used the maldistribution parameter, m, in their experimental study to know the influence of flow maldistribution and pressure drop across a plate heat exchanger.

$$m^2=\left(\frac{nA_c}{A}\right)^2\frac{1}{\zeta_c} \tag{9}$$

$$\zeta_c=\frac{2(\Delta P)_{\text{ch}}}{\rho {U_c}^2} \tag{10}$$

where n is no. of channels per fluid, A_c and A are cross-sectional area of channel and of port, respectively.

$$\zeta_c=\text{f}l/d_e+\text{ other losses} \tag{11}$$

Here, f is friction factor, l is vertical distance between two ports and d_e is equivalent diameter of the port.

A number of experiments had been conducted by them for the range of Reynolds number from 700 to 800. It was found that at normal values of port size the value of flow maldistribution parameter is close to zero, indicating a good flow distribution. As the effective port diameter is reduced to half its normal value, the flow distribution changes considerably with flow rate. They

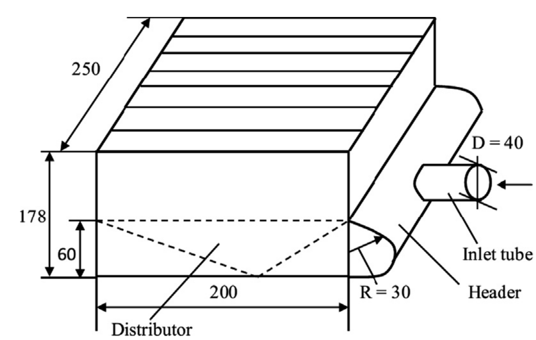

Fig. 5. PFHE modeled by Zhang and Li [25].

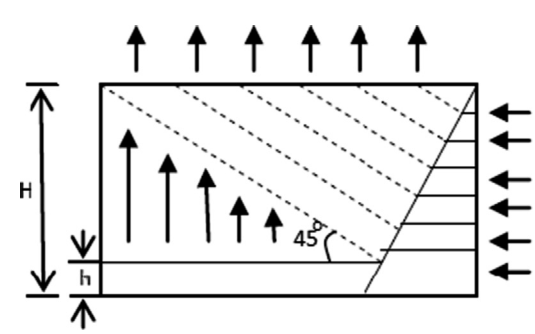

Fig. 6. Schematic interior view of a typical distributor [29].

also found that with the decrease in port size, the pressure drop increases due to maldistribution.

The effects of distributor configuration on flow maldistribution in plate-fin heat exchanger have been experimentally investigated by Jiao and Baek [29]. A correlation between the dimensionless flow maldistribution parameter (S) and the Reynolds number is obtained for different distributor configuration parameters (h/H=0, 0.1, 0.2 and 0.3). The experimental studies prove that the performance of heat exchangers can be effectively improved by the optimum design of the distributor's configuration parameter. Fig. 6 shows the schematic interior view of a typical distributor having 45° flow inlet angle. The definition of distributor configuration parameter (h/H) has also been denoted.

Different passage flow velocities directly affect the performance of flow distributor and hence that of heat exchangers. To calculate flow passage velocity and to evaluate the flow maldistribution they used the formula as specified in Eqs. (12)–(15).

Flow passage velocity,

$$\vartheta = Q/(A\tau) \tag{12}$$

For the evaluation of flow maldistribution, three parameters have been used as defined by $\delta\vartheta_i/\vartheta_{ave}$, $\vartheta_{\max}/\vartheta_{\min}$ and S.

$$\delta\vartheta_i = \vartheta_i - \vartheta_{ave} \tag{13}$$

$$\vartheta^2 = \frac{1}{A}\int_0^x \int_0^y \left[\frac{\vartheta_{x,y}}{\vartheta_{ave}} - 1\right]^2 dx\, dy \tag{14}$$

$$S = \left[\frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{\vartheta_i}{\vartheta_{ave}} - 1\right)^2\right]^{1/2} \tag{15}$$

where N stands for the passage number.

The parameter, ϑ, could be used to evaluate the flow maldistribution if the equation of flow velocity distribution is known. However, the flow velocity distribution can hardly be obtained, so the dimensionless standard deviation 'S' of the sample has been used instead to represent the characteristic of flow maldistribution. The experimental result shows that the distributor's performance, with its h/H value equal to 0.2, is the best.

As flow distribution considered by Chiou [19] is not a generalized one and is applicable for a particular geometry only, different researchers [23,41 and 78] have considered different models for maldistribution in various heat exchangers.

Effects of flow maldistribution on the thermal performance of a three-fluid crossflow heat exchanger have been numerically studied by Yuan [78]. Three flow maldistribution models with four modes (UUU, AAA, CAB and BAC) of flow nonuniformity arrangements in the inlets of fluid streams were considered. Fig. 7 shows the profiles of inlet flow nonuniformity. These are cited from models B and C by Chiou [79], which were obtained directly from wind tunnel experiments. Models C, A and B have been selected as the inlet flow maldistribution of fluid streams 1, 2 and 3, respectively. The thermal performance has been found to be in decreasing order for four modes UUU (without flow maldistribution), AAA, CAB and BAC in most of the cases but the thermal performance for modes AAA and CAB have been found to be higher than modes UUU in some case. Thus it was observed that when flow maldistribution occurs on three fluid sides, the thermal performance may be greater or less than when all fluid side in uniformly distributed. The thermal performance for mode BAC was found to be the worst while it was the best for mode CAB.

Chowdhury [80] proposed a beta distribution model of first kind for a numerical behavior of the maldistribution. This model is a good alternative as it is of single mode, has finite limits and has the tendency to be skewed positively or negatively. The model proposed by Mishra et al. [3] could be utilized as a general one if the proper value of $\beta(p, q)$ is considered.

The Beta function $\beta(p, q)$ of the parameters p and q has been defined as

$$\beta(p,q) = \int_0^1 \left[y^{p-1}(1-y)^{q-1}dy\right] \tag{16}$$

The mass flow rate of the fluid moving in the x direction has been assumed to follow the Beta distribution of first kind, which is given as

$$f(y) = \frac{1}{\beta(p,q)}\left[y^{p-1}(1-y)^{q-1}\right], 0 \le y \le 1 \tag{17}$$

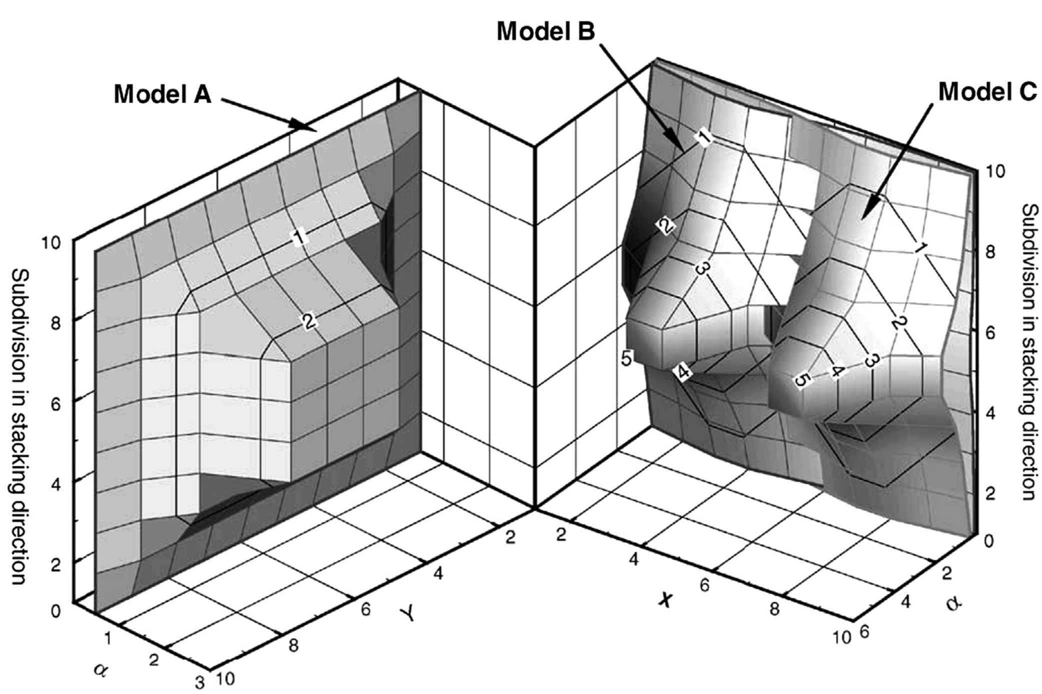

Fig. 7. Flow maldistribution model [78].

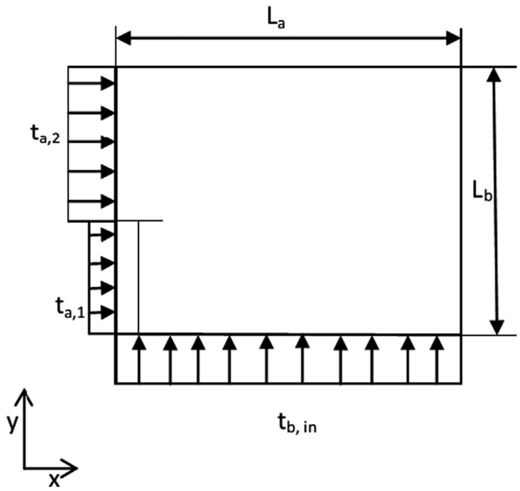

Fig. 8. Schematic diagram showing nonuniformity in temperature at the entry to fluid 'a' [10].

4.2. Temperature nonuniformity models

Nonuniformity in fluid temperature at inlet to compact heat exchanger may also affect its thermal performance. The steady state performance of crossflow heat exchanger has been studied by Kou and Yuan [10]. However, the transient performance also cannot be ignored as studied by Mishra et al. [3]. The temperature nonuniformity as shown in Fig. 8 represents two level temperature distribution for fluid 'a' while fluid 'b' is given uniform entry. It was found that the mean exit temperature of both fluids and hence the performance of heat exchanger gets affected.

5. Effect of phase change

The flow maldistribution problems in evaporators are the most severe when the major fraction of the pressure drop occurs in the two-phase region and cannot be prevented in some cases (reboilers and evaporators). However, in most heat exchangers with such problems, the economic penalty for maldistribution is small, and deterioration of the thermal performance is slightly affected [81]. But, flow maldistribution problems in condensers may be very severe and should not be underestimated [82]. Maldistribution due to two-phase flow may be caused and/or influenced by phase separation, oscillating flows, variable pressure drops (density-wave instability), flow reversals, and other flow instabilities [1].

Bai and Newell [83] studied two-phase flow visualization characteristics in chevron-style flat plate heat exchangers and obtained some photographs of flow maldistribution showing phase separation. Vist and Pettersen [84] also carried out an experimental study to investigate two-phase flow distribution in compact heat exchanger manifolds. They investigated the effects of various factors like vapor fraction at the manifold inlet, heating load, diameter and tube length on flow distribution.

Marchitto et al. [85] carried out several experiments on a horizontal cylindrical two-phase flow header supplying sixteen vertical channels. The flows inside the vertical channels were kept upward. Measurements of air-water flow rate distributions were taken for a number of operating conditions and for different geometrical configurations. Video clips have been taken to visualize flow patterns inside the distributors and two-phase flow distributions from intermittent to annular flow. Experimental results showed that the operating conditions exerted a strong influence on the structure of the two-phase flow pattern inside the header and therefore on the flow distribution to the channels.

Experimental investigation of two-phase maldistribution in different header channels of a compact heat exchanger was carried out by Ahmad et al. [86]. Several geometrical and functional parameters were tested to study two-phase distribution at a temperature and pressure close to 57 °C and 100 kPa, respectively. Flow patterns and two-phase distribution inside header were also investigated.

The two-phase flow distribution in a plate fin heat exchanger has also been experimentally studied by Wang et al. [87] under different operating conditions. It was found that the maldistribution of two-phase flow is very serious in conventional heat exchanger used in industries due to an improper header configuration. The distribution of single phase flow is markedly different from that of the two-phase flow. They suggested that the improved header with perforated baffle can effectively improve the uniformity of two-phase flow distribution in both ordinate and crosswise directions compared to a conventional header.

Experimental investigation by Saad et al. [88] was carried out for two-phase offset strip plate-fin type compact heat exchanger considering flow maldistribution. Air and water were used as working fluids. The flow rates of each phase in the seven zones regularly distributed at the outlet as well as the pressure at the inlet, the outlet and the two intermediate positions have been measured (Fig. 9). An empirical correlation for single phase friction factor in offset strip fins has been established for laminar to turbulent flow of water and air and compared with simulation results using computational fluid dynamics:

$$f = 20.362 \mathrm{Re} D_h^{\;-0.7661} \tag{18}$$

With a high-speed camera, two-phase flow regimes have been investigated and a flow map was established. Saad et al. [89] further conducted experiments and carried out CFD simulation for single-phase flow in a compact heat exchanger in order to study the flow behavior. The pressure drop of single phase flow was analyzed in a preliminary step. In the second step, the two phase flow distribution at the outlet was characterized using air and water as working fluids and for different operating conditions. They found that the distributors of the two-phase flow in the compact heat exchanger depend on the gas and liquid superficial velocities. The effect of liquid flow rate on the distribution is less important than the effects of gas flow rate. When the gas superficial velocity increases, gas distribution at the outlet becomes more uniform.

Further, an experimental investigation was carried out by Marchitto et al. [90] for understanding the main mechanisms of the flow distribution inside a two-phase horizontal header in order to improve and to optimize the flow distribution inside compact heat exchanger. The study was carried out with air–water mixtures and was based on the measurement of flow rates in individual channels and on pressure drops across the distributor. The effects of the operating conditions, the header/flute geometry and of the inlet nozzles were investigated for a range of liquid and gas superficial velocities. The results indicated the flute geometry as a promising configuration to improve flow rate uniformity inside parallel channels.

6. Effect of variations in physical properties

Heat transfer to (or from) the fluids in turbulent flow through smooth pipes with moderate property variation was investigated by Ibrahim and Walker [91]. The objective was to extend constant property eddy diffusivity models to variable property pipe flow in a systematic way and to compute the effects of the variations of c_v, k, ρ and μ separately and in combination for the range of R_e and P_r. This has been achieved to an extent but with the growing realization that eddy diffusivity models, even for constant properties, lack a logical foundation so that their extension to variable

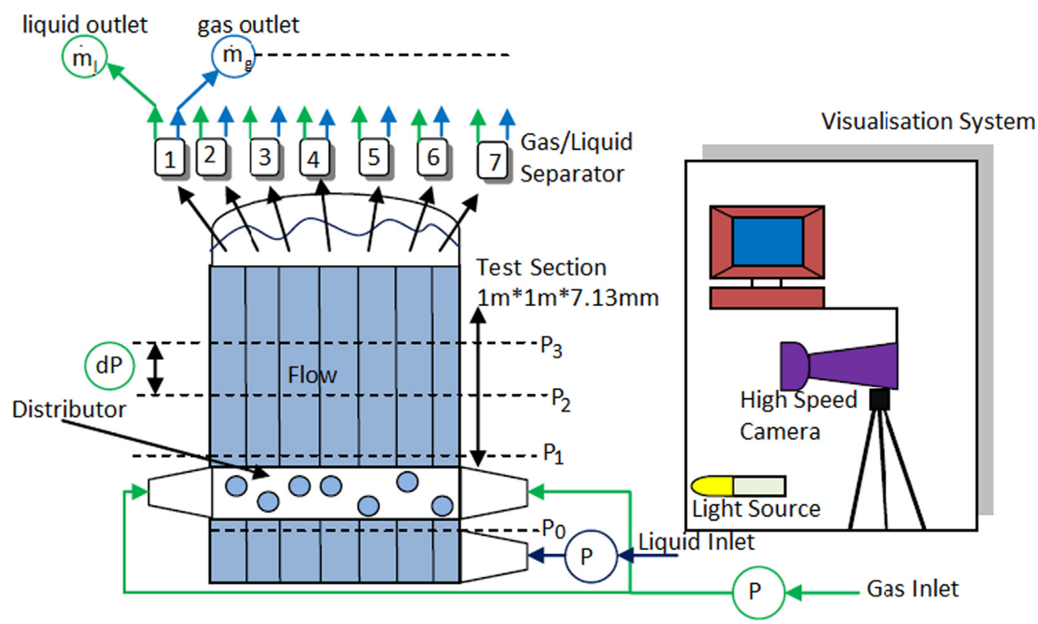

Fig. 9. Scheme of experimental setup [88].

properties must be equally arbitrary. Nevertheless, theoretical results derived from the models yielded design predictions at least as reliable as could be obtained by direct use of the multiplicity of unsatisfactory and contradictory experimental correlations.

Thermo-physical properties may also vary due to maldistribution in compact heat exchanger. In general, the analyses carried out by researchers are for the dynamic behavior of heat exchanger considering constant values of heat transfer coefficients, thermal conductivities, heat capacities, etc. In fact, these properties vary with change in temperature and vapor fraction in case of two-phase flow. This presents a significant deviation from the constant property assumptions in analyses. The property ratio approach is the most commonly used method to take into account the fluid property variations in the heat exchanger. According to this approach, Nusselt number and friction factors for the variable fluid property cases are related to the same for constant-property values for gases and liquids [1] as given in Eqs. (19, 20).

$$\text{For gases}: \quad \frac{Nu}{Nu_{cp}} = \left(\frac{T_w}{T_m}\right)^n \quad \frac{f}{f_{cp}} = \left(\frac{T_w}{T_m}\right)^m \tag{19}$$

$$\text{For liquids}: \quad \frac{Nu}{Nu_{cp}} = \left(\frac{\mu_w}{\mu_m}\right)^n \quad \frac{f}{f_{cp}} = \left(\frac{\mu_w}{\mu_m}\right)^m \tag{20}$$

Here, the subscript cp refers to the constant property, all the temperatures are in absolute K and all the properties are evaluated at the bulk mean temperature. The exponents 'n' and 'm' depend upon the heating/cooling situations of the fluid.

A numerical model was developed as a callable sub-routine as well as a stand-alone program by Nellis [92] incorporating property. Numerical solutions were carried out using relaxation techniques together with sparse matrix decomposition over an exponentially distributed grid.

The coupled energy equations for both sides of a heat exchanger were solved by Naterar and Lam [93] using an integral method taking variable convection coefficients due to changes in vapor fractions between inlet and outlet of the heat exchanger.

A study was also carried out by Bobbily et al. [94] evaluating the thermal performance of falling film plate condensers with flow maldistribution from port to channel considering the heat transfer coefficient inside the channels as a function of channel flow rate. They have presented a generalized mathematical model to study the effect of maldistribution. The model predicts the behavior of the plate condensers in a physically consistent way under the flow maldistribution from port to the channel.

An analysis of real situations has been carried out by Sharqawy and Zubair [95] using analytical and numerical approaches. An example has been solved using different approaches to calculate the surface area of a heat exchanger when the overall heat transfer coefficient is not constant.

Gulhane and Mahulikar [96] used compressible laminar fluid flow, incorporating different combinations of $\rho(p, T)$, $Cp(T)$, $k(T)$ and $\mu(T)$ leading to non-rarefaction scaling effects. It is noticed that Nu deviates significantly from constant property solution, especially at the beginning of the computational domain, although this difference reduces as the flow proceeds. The effect of $\rho(p, T)$ and $\mu(T)$ on convective flow is indirect and deviation in Nu is significant through velocity field, while deviation due to $Cp(T)$ and $k(T)$ is significant through temperature field.

7. Nonuniformities in three-fluid heat exchanger

A wide literature is available on the steady state behavior of three-fluid heat exchanger [97,98] dealing with thermal design theory. Work carried out by researchers regarding nonuniformities in two-fluid compact heat exchangers are still significant but only a few literature is available focusing on the analysis of flow maldistribution in three-fluid compact heat exchangers. The complicated arrangement of fluid streams in three-fluid heat exchanger, design and manufacture of headers and distributors are mainly responsible for generating the nonuniformities in inlet temperature and flow. Hence, the effect of maldistribution on the thermal performance of a three fluid heat exchanger cannot be ignored.

Yuan [78] investigated the effect of flow maldistribution on the steady-state performance of a three-fluid crossflow heat exchanger using a finite difference method. At the inlets of three fluid streams, different flow maldistribution models were considered and it was found that the maldistribution considerably affects the steady state thermal performance of three-fluid heat exchanger.

A few literatures are also available on the transient performance of three-fluid crossflow heat exchanger with temperature

nonuniformity. The transient temperature response of the three-fluid crossflow heat exchanger has been numerically investigated by Mishra and Sahoo [99] for step change in inlet temperature of central fluid. Temperature nonuniformity has been considered in the central fluid. A typical case of co-current crossflow three-fluid heat exchanger with finite core capacity was analyzed using the finite difference technique. Further, Mishra [100] numerically investigated the transient temperature response of a co-current crossflow three-fluid heat exchanger with flow nonuniformity. Flow nonuniformity with beta flow maldistribution model has been considered in the hot fluid. Mathematical model for three-fluid crossflow heat exchanger with four possible arrangements has been made and the solution was obtained using implicit finite difference technique [101].

Mishra et al. [102] have considered the nonuniformity only in central fluid (b) and the other two fluids are assumed to be uniformly distributed in the four flow arrangements. Both temperature [99] and flow nonuniformity [100] have been proposed. The value of 'α', flow maldistribution factor, ($\alpha = m'/m$) has been taken from one-dimensional Beta distribution model of the first kind [80]. Results have also been depicted for the variation of mean exit temperature of three fluids for step change in central fluid with flow nonuniformity. The exit temperature responses were also found dependent on the position of fluid moving device for the three fluids.

Apart from temperature and flow nonuniformities in compact heat exchangers, heat exchanger with transfer coefficient varying with temperature or length of flow path as shown by Peters [103]; the nonuniformity in overall heat transfer coefficient as deduced by Shah and Sekulic [104] has also been investigated.

8. Effect of flow maldistribution in solar collectors

Sun is the renewable and sustainable source of energy on Earth which radiates solar energy about 15,000 times the total energy consumed per year worldwide [105]. The technologies to trap abundant solar energy are still either at infancy or economically unviable. Only a few of the technologies like solar water heater and photovoltaic cell are fully commercialized.

A solar water heater extracts thermal energy radiated by the sun for various purposes like domestic water heating, space heating, pool heating, etc. Solar collector is the core component of a solar water heater. A flat plate solar collector generally consists of a tube and fin geometry through which fluid passes. Report on the investigation of the effect of flow nonuniformity on the solar collector performance is very scarce [106]. Analysis of the performance of solar collector panel is normally based on the assumption of uniform flow distribution in all the tubes [107]. The fluid flow distribution in the tubes is, however, usually not uniform under normal operating conditions. The deterioration of collector efficiency can be more than 20% due to flow maldistribution [19]. It has also been observed that deterioration of the collector efficiency becomes quite significant if some tubes are completely plugged up or choked. So it is recommended that flow maldistribution effect be considered in the analysis and design of solar collectors.

Many works have been reported considering the effect of flow maldistribution on the thermal performance of solar collector, including Duffie and Beckman [108] for the design of flat plate collector; Jones and Lior [109] for negligible buoyancy effects; Gunnewiek et al. [110,111] on increase of collector efficiency due to flow nonuniformity; Weitbrecht et al. [112] with laminar flow conditions; Karwa et al. [113] for the flow maldistribution caused by the imperfections and tolerances on the thermal performance of a solar heater array and Fan and Furbo [114] for fluid flow and heat transfer in the collector panel with the buoyancy effects. But still a lot more efforts are needed in this area.

9. Conclusions

Compact heat exchangers play an important role in saving and utilizing energy with high efficiency. In the coming years, increasing demand for compact heat exchanger complying with the principles of ecological and economic sustainability will certainly further expand their industrial applications. The effects of temperature and flow nonuniformity on the performance of compact heat exchangers have been reviewed along with the effects of a few non-dimensional parameters such as local flow nonuniformity parameter, Φ, distributor configuration parameter (h/H), etc. It has been observed that in compact heat exchanger, flow and temperature nonuniformity degrade the performance. The magnitude of deterioration in thermal performance is found to be dependent on the distribution model, i.e. the position of the fluid moving device with respect to the heat exchanger axis and the temperature distribution pattern. It is found that their effects are vital in the analysis of compact heat exchanger. As exact analytical solutions are not feasible, numerical and experimental techniques play a vital role.

According to various studies, the effect of flow maldistribution on the thermal performance of a two-fluid crossflow heat exchanger is severely detrimental which cannot be neglected. Maldistribution in a compact heat exchanger can lead to a loss of effectiveness of even more than 25%. It is found that the fluid flow maldistribution is very serious in the direction of header length for the conventional headers used in the industry due to poor header configuration. It has also been found that the deterioration of collector efficiency can be more than 20% due to flow maldistribution. Conventional methods used for the design and development of heat exchanger cores, manifolds and headers are largely tedious and may be expensive in today's competitive market. Computational fluid dynamics (CFD) has emerged as a cost-effective alternative and it provides speedy solution to heat exchanger design and optimization. Easily accessible general purpose CFD commercial software can fulfill the requirements of simulation of various types of heat exchangers including compact heat exchanger. The simulations generally yield results within good agreement with the experimental studies ranging from 2% to 10% while in some exceptional cases they may vary up to 36%.

10. Challenges ahead

- Very little attention has been given for the effects of longitudinal conduction, axial dispersion and maldistribution in case of three-fluid or multi-fluid compact heat exchanger. Proper design of headers and distributors is required to minimize these deteriorating effects in the thermo-hydraulic performance of compact heat exchanger. It has also been found that there has been few works focusing on the analysis of flow and/or temperature maldistribution in three-fluid or multi-fluid compact heat exchanger.
- CFD simulation may be a good option to investigate the extent of performance degradation and to rectify the problems accordingly, which otherwise cannot be handled analytically.
- Although CFD is capable of predicting and simulating the phenomena in compact heat exchangers with reasonable accuracy, parallel effort should be made for the experimental verification.
- A detailed analysis for the performance deterioration in compact heat exchangers due to two-phase flow and for variable thermo-physical properties is required.

- Investigations of flow maldistribution in devices like solar collectors are scarce, and the presented results are limited, unsystematic and even contradictory. Thus it is necessary to take due care in designing the solar collectors for reducing the flow maldistribution. Further, the effects of the arrangement of flow configurations, design parameters, and operating conditions on the flow maldistribution also need to investigated so as to extract the energy at its maximum.

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